

PERMEATION LAYER ATTACHMENT CHEMISTRY AND METHOD

FIELD OF THE INVENTION

5 This invention relates to the attachment of a layer of polymeric material to a substrate surface. More particularly, this invention relates to chemistries and methods for covalently attaching a porous polymeric material to an electrically conductive substrate, such as a metal electrode of a microchip circuit.

BACKGROUND OF THE INVENTION

10 The following description provides a summary of information relevant to the present invention. It is not an admission that any of the information provided herein is prior art to the presently claimed invention, nor that any of the publications specifically or implicitly referenced are prior art to the invention.

15 In the art of electronically addressable microchips that are used to direct biomaterials, such as nucleic acids and proteins, from one point in a solution to another, the microchips should be designed so that electric potential from the microchip electrodes will translate to the solution overlying the microchip such that any electrochemistry occurring from the electrode surface will neither damage the electrodes themselves, nor any biomaterials in the solution. Generally, protection from such damage is provided by the use of a porous membrane layer deposited over the microchip electrodes. Usually, such layer comprises materials derived from natural or synthetic polymers such as agarose or polyacrylamide, respectively. These types of materials allow electrochemical products generated at the electrode surface to travel through their porous matrix or 'permeation layer' and into the solution immediately above the electrodes.

20 Although materials such as those noted above have been found useful in the role of a porous membrane having desired qualities, it has been found that because of the methodologies commonly used to layer such membranes onto the microchip substrate, the membranes are prone to separate or 'delaminate' from the electrode surface. It is believed this delamination is caused by a change in the chemical make-up at the interface between the permeation layer and the electrode resulting from the application of electronic potential at the electrode and by physical disruption from charged ions and gases emanating from the electrode. Such delamination can be viewed from the standpoint of 'microdelamination' and 'macrodelamination'.

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Microdelamination involves the electrochemical degradation of the chemical interface between the permeation layer and the electrode itself. It is observed by the formation of raised bulges in the permeation layer, or by ringlets visible due to defraction of light from the delaminated layer when appropriately viewed by a confocal microscope and results in the loss of consistency in permeation layer performance (possibly due to the loss of control over the electric field uniformity). Macrodelamination, on the other hand, is caused by a mismatch of the surface energies between the permeation layer and the chip substrate and results in permeation layer peeling (lift-off) which can extend across the entire microchip surface. Since the permeation layer provides a means for chemical anchorage of analytes present in the liquid overlay, its physical loss by macrodelamination results in catastrophic chip failure during bioassays.

Electronically addressable systems such as the microchips considered herein follow Ohm's law which establishes the relationship between the voltage drop (V) between two electrodes (i.e., the anode, placed at a positive potential and the other, the cathode, placed at a negative potential), and the electric current (I) which flows between these electrodes, as follows:

$$V = R \times I \quad (1)$$

where R is the electrical resistance of the medium between the anode and the cathode. In systems where a permeation layer is present over such electrodes, the value of R is greatly determined by the physical and chemical nature of said permeation layer. Thus, according to formula (1), the difference between the electronic potentials applied to the electrodes is directly proportional to the intensity or density of the electric current which flows through them. The invention described in this Letters Patent uses a relationship between electric current and voltage wherein electric current densities are at least 0.04 nA/ μm^2 and/or voltage drops are between 1 and 3 V. The electric current density is defined as the electric current divided by the area of the electrode used to support it.

Additionally, the effectiveness of the translocation of charged biomolecules such as nucleotide oligomers within an electronically-driven system such as that described herein depends on the generation of the proper gradient of positively and negatively charged electrochemical species by the anode and cathode, respectively. For example, effective nucleic acid (i.e. either DNA or RNA) transport may be accomplished by generation of protons and

hydroxyl anions when the potential at the anode is greater than +1.29 V with respect to a 'saturated calomel electrode' (SCE). When subjected to such demanding operating conditions, noncovalently-attached permeation layers prove to be unsatisfactory since such systems are likely to experience micro- and sometimes macrodelamination. Moreover, the transport efficiency of charged molecules increases with increasing current density, thus driving the desire for operation at higher voltage drops and current densities and, thus, the need for evermore robust permeation layers.

Therefore, a need still remains for methodologies for keeping permeation layers from delaminating from electronic microchip substrates and particularly from the electrode pads themselves. We have discovered an improvement in permeation layer attachment chemistry that provides a significant increase in permeation layer performance. Specifically, we have solved the problem of micro- and macrodelamination by discovery of a covalent chemistry linkage system that, as applied to electronically addressable microchip art, can be incorporated between the microchip and the permeation layer matrix. This chemistry is applicable to a variety of permeation layer compositions, including polymers, hydrogels, glyoxylagarose, polyacrylamide, polymers of methacrylamide, materials made from other synthetic monomers, and porous inorganic oxides created through a sol-gel process, and is able to withstand current densities of at least $0.04 \text{ nA}/\mu\text{m}^2$ and/or voltage drops between 1 and 3 V.

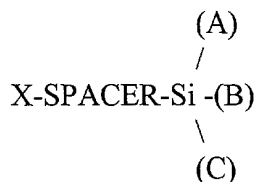
SUMMARY OF THE INVENTION

The current invention provides a unique system for the covalent attachment of a porous 'permeation layer' to the surface of electronically addressable microchips. In a preferred embodiment, the covalent attachment is between chemical moieties of the permeation layer and metal/silicide, metal/metal, or organic electrodes. Preferred metal/silicide electrodes include platinum silicide (PtSi), tungsten silicide (WTi), titanium silicide (TiSi), and gold silicide (AuSi). Preferred metal/metal electrodes include platinum/titanium (PtTi) and gold/titanium (AuTi). Preferred organic electrodes include materials such as poly(phenylene vinylene), polythiophene, and polyaniline.

In an example of this embodiment, the covalent attachment comprises a linking moiety that provides an attachment mechanism for bonding the linker to the silanol moiety of a metal/Si surface and a separate moiety for bonding the linker to the permeation layer. Where metal/metal

and organic electrodes are employed, the attachment mechanism of the linker to the electrode is the same in that the moiety of the linker attaching to the electrode will react with specific metals and reactive centers on organic molecules to form covalent bonds.

In a particularly preferred embodiment, the linking moiety is defined by the formula:



where X= acrylate, methacrylate, acrylamide, methacrylamide, allyl, vinyl, acetyl, amine (substituted or not), epoxy or thiol;

SPACER= alkyl, aryl, mono- or polyalkoxy (such as ethyleneglycol or polyethyleneglycol), mono- or polyalkylamine, mono- or polyamide, thioether derivatives, or mono- or polydisulfides;

A and B= any combination of Oxygen-R, where R= H, alkyl such as methyl, ethyl, propyl, isopropyl or other linear or branched hydrocarbon, Cl, Br or a moiety functionality similar to that of X-SPACER; and

C= Oxygen-R, where R= H, alkyl such as methyl, ethyl, propyl, isopropyl or other linear or branched hydrocarbon, Cl, Br, or any other hydrolyzable moiety.

In the example of the metal/Si electrodes, these linkage groups, which contain a silicide group can react with hydroxyl groups bonded to an oxygen moiety of the electrode surface. On the other end of the linker, the X moiety comprises chemical groups that are available to covalently react with reactive centers of the permeation layer polymer.

In another embodiment, the permeation layer is a material suitable for transmitting electronic charge from an electrode to a solution overlaying the electrode. Materials contemplated for constructing polymers used for the permeation layer may include, but are not limited to, agarose, glyoxylagarose, acrylamide, methacrylamide, polyacrylamide, materials made from other synthetic monomers, hydrogels, and porous inorganic oxides created through a sol-gel process (Brinker et al., *Sol-Gel Science*, Academic Press, San Diego, 1990).

Synthetic monomers used to make polymeric permeation layers may include those selected from the group consisting of epoxides, alkenyl moieties including, but not limited to, substituted or unsubstituted α , β unsaturated carbonyls wherein the double bond is directly attached to a carbon which is double bonded to an oxygen and single bonded to another oxygen, nitrogen, sulfur, halogen, or carbon; vinyl, wherein the double bond is singly bonded to an oxygen, nitrogen, halogen, phosphorus or sulfur; allyl, wherein the double bond is singly bonded to a carbon which is bonded to an oxygen, nitrogen, halogen, phosphorus or sulfur; homoallyl, wherein the double bond is singly bonded to a carbon which is singly bonded to another carbon which is then singly bonded to an oxygen, nitrogen, halogen, phosphorus or sulfur; and alkynyl moieties wherein a triple bond exists between two carbon atoms.

In another embodiment, the covalently attached permeation layer is kept from delaminating while the anode is charged with an electronic potential above +1.29V/SCE and/or the cathode with a potential below -0.89 V/SCE. In a particularly preferred embodiment, the current flow between the electrodes has a density sufficient to induce the transport of molecules in the solution above the electrodes of the microchip. Such density is preferably at least 0.04 nA/ μm^2 .

BRIEF DESCRIPTION OF THE DRAWINGS

The file of this patent contains at least one drawing executed in color. Copies of this patent with color drawing(s) will be provided by the Patent and Trademark Office upon request and payment of the necessary fee. The invention will be further described with reference to the accompanying drawings in which:

Figure 1 is a chemical structure schematic showing attachment of a linker moiety to the electrode surface.

Figure 2 is a schematic diagram showing a process for covalent attachment of the permeation layer to the electrode. In the example of the figure, the electrode is treated with an argon plasma for 5 minutes at 250 mTorr (250W). This cleans the electrode, which has hydroxyl functionalities at its surface. Linker is then attached to the electrode such as by vapor deposition for 5 minutes at room temperature followed by curing at 90°C for 2 hours. This process leaves reactive moieties that can bond to the permeation layer. In the example of the figure, a linker having reactive amine groups is used wherein the amine moieties are available for bonding to

reactive moieties of the permeation layer matrix. The bonding between the linker and permeation layer reactive centers can be accomplished using a Schiff base reaction.

Figure 3A and B are confocal microscope photos of partial images of individual electrodes wherein the permeable membrane attached to the electrode surface without use of a linker moiety is shown before (A) and after (B) delamination.

Figure 4A-D are confocal microscope photos of partial images of individual electrodes wherein the permeable membrane attached to the electrode surface using AEAPS deposited by vapor is shown at various degrees of delamination.

Figure 5A and B are confocal microscope photos of partial images of 80 μm diameter Pt (A) and a PtSi (B) electrodes wherein the permeable membrane was attached to the electrode surface using AEAPS. In Fig. 5A, the Pt electrode began to delaminate at the second direct current impulse of 500 nA ($0.1 \text{ nA}/\mu\text{m}^2$) for 2 min. In contrast, (Fig. 5B) the PtSi electrode showed no delamination after the second direct current impulse of 500 nA ($0.1 \text{ nA}/\mu\text{m}^2$).

Figures 6A and B, and 7A and B are confocal microscope photos of partial images of electrode arrays wherein the permeable membrane was either deposited on a Pt electrode without chemical attachment (6A and 7A) or was attached to a PtSi electrode surface using AEAPS (6B and 7B). The images show the levels of repeated biasing that result in delamination for Pt without covalent bonding of the permeation layer and PtSi microchips with covalent bonding.

Figures 8, 9, and 10 are confocal microscope photos of partial images of a Pt electrode overlaid with agarose. In Fig. 8 the focal plane of the image is set at 3 μm above the electrode prior to electronic biasing. This indicates the permeation layer surface is 3 μm above the electrode as indicated by the beads being in focus. In Fig. 9 an unchanged focal plane during electronic biasing is shown. In Fig. 10, a focal plane 4 μm above the electrode is shown indicating that delamination occurred causing the permeation layer to rise so that the beads resting on top of the layer come into focus at a greater distance from the electrode.

Figure 11 is a confocal microscope photo showing confirmation that the permeation layer of Fig. 10 delaminated as indicated by the presence of concentric rings.

Figures 12 and 13 are confocal microscope photos of partial images of electrodes showing PtSi electrode with an acrylamide permeation layer covalently attached. Fig. 12 shows that the focal plane remained unchanged after a two-minute bias at +2 μA ($0.4 \text{ nA}/\mu\text{m}^2$). Fig. 13 confirms that no delamination occurred with this electrode.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In the art of electronically addressable microchips used for transporting charged molecules from one point in a solution to another, the transported molecules must be protected from direct contact with the electrodes of the microchip and ions produced at the electrode when the electrodes are biased to impart an electric field to the solution. Protection is provided by an insulating membrane, i.e., the permeation layer, which also allows for the flow of charge from the electrode to the solution without damaging the transported molecules. Typically, the insulating membrane is a polymeric material such as agarose or cross-linked polyacrylamide. These materials are ideal in that they are porous and allow electrochemical products created at the electrode to escape to the overlying solution.

More specifically, such insulating membrane materials can comprise, but are not limited to, agarose, glyoxylagarose, acrylamide, methacrylamide, polyacrylamide, materials made from other synthetic monomers, and porous inorganic oxides created through a sol-gel process. Synthetic monomers used to make polymeric permeation layers may also include those selected from the group consisting of epoxides, alkenyl moieties including, but not limited to, substituted or unsubstituted α , β unsaturated carbonyls wherein the double bond is directly attached to a carbon which is double bonded to an oxygen and single bonded to another oxygen, nitrogen, sulfur, halogen, or carbon; vinyl, wherein the double bond is singly bonded to an oxygen, nitrogen, halogen, phosphorus or sulfur; allyl, wherein the double bond is singly bonded to a carbon which is bonded to an oxygen, nitrogen, halogen, phosphorus or sulfur; homoallyl, wherein the double bond is singly bonded to a carbon which is singly bonded to another carbon which is then singly bonded to an oxygen, nitrogen, halogen, phosphorus or sulfur; and alkynyl moieties wherein a triple bond exists between two carbon atoms.

As described above, for optimal functionality of electronically addressable microchips, it is important that the porous insulating layer or permeation layer remain in contact with the electrode in order to enhance uniformity and consistency of the electronic potential from one pad to the other. As shown in Figure 1 the permeation layer may be linked to the electrode by a linking moiety that has at least two reactive centers. Linkers having suitable characteristics such as that shown in Fig. 1 are provided in Table I.

Table I

CHEMICAL TYPE	FORMULA
5 ACRYLATES:	$\text{CH}_2=\text{CHCOOCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$ $\text{CH}_2=\text{CHCOOCH}_2\text{CH}_2\text{CH}_2\text{SiCl}_3$ $\text{CH}_2=\text{CHCOOCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{CH}_3)(\text{OCH}_3)_2$ $\text{CH}_2=\text{CHCOOCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{CH}_3)_2(\text{OCH}_3)$ $\text{CH}_2=\text{CHCOOCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{CH}_3)\text{Cl}_2$ $\text{CH}_2=\text{CHCOOCH}_2\text{CH}(\text{OH})\text{CH}_2\text{NHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OC}_2\text{H}_5)_3$
10 METHACRYLATES:	$\text{CH}_2=\text{C}(\text{CH}_3)\text{COOCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$ (MOTS) $\text{CH}_2=\text{C}(\text{CH}_3)\text{COOCH}_2\text{CH}_2\text{CH}_2\text{SiCl}_3$ $\text{CH}_2=\text{C}(\text{CH}_3)\text{COOCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{CH}_3)(\text{OCH}_3)_2$ $\text{CH}_2=\text{C}(\text{CH}_3)\text{COOCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{CH}_3)_2(\text{OCH}_3)$ $\text{CH}_2=\text{C}(\text{CH}_3)\text{COOCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{CH}_3)\text{Cl}_2$ $\text{CH}_2=\text{C}(\text{CH}_3)\text{COOCH}_2\text{CH}(\text{OH})\text{CH}_2\text{NHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OC}_2\text{H}_5)_3$
15 ACRYLAMIDES:	$\text{CH}_2=\text{CHCONHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OC}_2\text{H}_5)_3$ (AMPTS) $\text{CH}_2=\text{CHCONHCH}_2\text{CH}_2\text{CH}_2\text{SiCl}_3$ $\text{CH}_2=\text{CHCONHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{CH}_3)(\text{OCH}_3)_2$ $\text{CH}_2=\text{CHCONHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{CH}_3)_2(\text{OCH}_3)$ $\text{CH}_2=\text{CHCONHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{CH}_3)\text{Cl}_2$ $\text{CH}_2=\text{CHCONHCH}_2\text{CH}(\text{OH})\text{CH}_2\text{NHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OC}_2\text{H}_5)_3$ $\text{CH}_2=\text{CHCONHCH}_2\text{CH}_2\text{CONHCH}_2\text{CH}_2\text{CONHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OC}_2\text{H}_5)_3$
20 METHACRYLAMIDES:	$\text{CH}_2=\text{C}(\text{CH}_3)\text{CONHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$ $\text{CH}_2=\text{C}(\text{CH}_3)\text{CONHCH}_2\text{CH}_2\text{CH}_2\text{SiCl}_3$ $\text{CH}_2=\text{C}(\text{CH}_3)\text{CONHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{CH}_3)(\text{OCH}_3)_2$ $\text{CH}_2=\text{C}(\text{CH}_3)\text{CONHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{CH}_3)_2(\text{OCH}_3)$ $\text{CH}_2=\text{C}(\text{CH}_3)\text{CONHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{CH}_3)\text{Cl}_2$ $\text{CH}_2=\text{C}(\text{CH}_3)\text{CONHCH}_2\text{CH}(\text{OH})\text{CH}_2\text{NHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OC}_2\text{H}_5)_3$
25 ALLYL DERIVATIVES:	$\text{CH}_2=\text{CHCH}_2\text{NHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$ $\text{CH}_2=\text{CHCH}_2\text{SiH}(\text{OCH}_3)_2$ $\text{CH}_2=\text{CHCH}_2\text{Si}(\text{CH}_3)_2\text{Cl}$ $\text{CH}_2=\text{CHCH}_2\text{SiHCl}_2$ $\text{CH}_2=\text{CHCH}_2\text{Si}(\text{OCH}_3)_3$

AMINO DERIVATIVES: $\text{H}_2\text{NCH}_2\text{CH}_2\text{NHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$ (**AEAPS**)
 $\text{H}_2\text{NCH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{NHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$ (**AHAPS**)
 $\text{H}_2\text{NCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$ (**APS**)
 $\text{H}_2\text{NCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OC}_2\text{H}_5)_3$

EPOXY DERIVATIVES: $\text{CH}_2-\text{CH}(\text{O})\text{CH}_2\text{OCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$
 $\text{CH}_2-\text{CH}(\text{O})\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OC}_2\text{H}_5)_3$

In a particularly preferred embodiment, microchips having covalent attachment chemistry of the current invention use linkers denoted APS, AEAPS, AHAPS, MOTS, and AMPTS.

Figure 2 shows a schematic of one embodiment wherein AEAPS is used to bond the electrode to the permeation layer. In this example, the PtSi electrode microchip is first treated with an argon plasma for 5 minutes at 250 mTorr and 250 Watts. The chip is then treated with AEAPS by vapor deposition over 5 minutes at room temperature then cured onto the chip by heating for 2 hours at 90°C. This causes the linker to covalently bind to the hydroxyl groups of the silicide moiety in the PtSi electrode. Once the linker is attached to the microchip, the permeation polymer (for example glyoxylagarose) is overlaid onto the electrode surface and treated in the presence of NaBH_3CN so that a Schiff base reaction and reduction can occur and cause the amine groups of the AEAPS linker to bond to the aldehyde functionality available on the permeation polymer (e.g., glyoxylagarose). Where polyacrylamide is employed as the permeation layer polymer, a UV-initiated free radical polymerization reaction can be conducted between the monomers which will make up the permeation layer and the vinyl moieties present at the surface of MOTS- or AMPTS linker-derived electrodes, thereby synthesizing the permeation layer and covalently anchoring it to the electrode in a single step.

Examples are provided below showing various delamination thresholds after attachment of the permeation layer using various linkers and attachment reaction conditions.

Example 1

Agarose permeation layer matrix was attached to a PtSi electrode microchip following deposition of either APS or AEAPS by one of two methodologies.

APS and AEAPS were deposited by exposure of the chip to a 0.1 wt % silane/dry MeOH solution for 1 hour at room temperature. The chips were rinsed in EtOH and cured at 90°C for 1 hour. In parallel experiments, APS and AEAPS linkers were deposited onto microchips by a vapor of neat silane in humid atmosphere for 5 min. at room temperature followed by a two hour cure at 90°C.

After the agarose permeation layer was attached, the microchips were subjected to electronic assays wherein the electrodes were biased with three direct current (DC) impulses for 2 minutes each at 200, 500, 700, and 1000 nAmps/ 80 μ m pad (i.e., 0.04, 0.10, 0.14 and 0.20 nA/ μ m²) using a model 236 Source-Measure unit (Keithley Instruments Inc., Cleveland, OH). Following the set of three DC impulses, the electrodes were biased with a sequence of 150 negative pulses, each comprised of a 0.1 sec. ON state at -0.2 nA/ μ m², followed by a 0.2 sec. OFF state at 0 nA/ μ m². As shown in Table II, the attachment schemes using vapor deposition of the linkers provided protection from delamination up to DC impulses of 700 nA for an 80 μ m electrode (0.14 nA/ μ m²).

Table II

samp		200 nA	200 nA	200 nA	-1uA	500 nA	500 nA	500 nA	-1uA	700 nA	700 nA
		DC1	DC2	DC3	AC	DC1	DC2	DC3	AC	DC1	DC2
A	PtSi (no perm layer)	+	+	+	+	+	+	+	+	+	+
B	PtSi /perm layer(no linker)	+	+/-			+/-	-	-	-	-	-
C	PtSi/APS/ perm layer(dry MeOH deposited)*					+	+	+/-	-	-	-
D	PtSi/AEAPS/ perm layer(dry MeOH deposited)*	+	+	+	+	+	+/-	-	-	-	-
E	PtSi/ APS/ perm layer(vapor deposited)*					+	+	+	+	+	+/-
F	PtSi/ AEAPS/					+	+	+	+	+	+/-

	perm layer(vapor deposited)*										
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+ = no delamination

+/- = initial indication of delamination

- = delamination resulting in decoupling of layer from pad.

* = the method of deposition applies to the silane, not the permeation layer

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As shown in Figures 3 and 4, delamination will occur at low levels of DC (200 nA (0.04 nA/ μm^2) after second DC pulse) where no covalent linker attachment is used to anneal the permeation layer to the electrode (Figs. 3A and B). Conversely, where AEAPS is used that has been applied to the electrode using vapor deposition, the delamination does not appear until the electrode has been exposed to the second DC pulse at 700 nA (0.14 nA/ μm^2) (delamination extended to 25% of the pad area at 3 min. past shut-off) with complete delamination by 2 minutes past third DC shut-off (Figs. 4A-D).

Example 2

In this example, delamination of the permeation layer from the electrode was tested using a multilayer permeation layer wherein the layers were applied using spin coating techniques then reacted to cause the linking moieties to covalently bond the layers together and to the electrode.

Specifically, microchips having PtSi electrodes were cleaned with oxygen plasma for 10 minutes followed by argon plasma for 10 minutes. AEAPS was then vapor-deposited for 5 minutes followed by curing at 90°C under vacuum. Subsequently, a first layer solution comprising 2.5% glyoxylagarose solution (NuFix) which had been stirred for 10 minutes at room temperature then boiled 7 minutes followed by filtering at 1.2 μm into the ASC device reservoir at 65°C, was spin-deposited onto the microchips with an automatic spin-coating device (ASC). Following deposition of the first layer, a second layer, comprising streptavidin (Scripps Laboratory, San Diego) at 5 mg/ml in 10 mM sodium phosphate, 250 mM NaCl (pH 7.2) which was filtered at 0.2 μm into the ASC reservoir and maintained at room temperature, was deposited similarly. The bottom layer was spin-coated at either 1500 or 2500 rpm, while the top layer was spin-coated at 5,000 rpm. The reaction for the reduction of the Schiff bases generated between streptavidin and glyoxylagarose, and between the AEAPS surface and glyoxylagarose was carried out by treating the coated microchip with 0.2 M NaBH_3CN 0.1 M sodium phosphate (pH

7.4) for 1 hr. at room temperature. Capping of the unreacted sites was performed by application of 0.1 M Gly/0.1 M NaBH₃CN, 0.1 M sodium phosphate (pH 7.4) to the chip for 30 minutes at room temperature. Finally, the treated microchip was exhaustively rinsed and soaked in deionized water for 30 minutes and then air dried overnight at room temperature.

5 As shown in Table III below, the thickness of the double permeation layer was examined where the substrate contained either plain platinum electrodes or PtSi electrodes using two different rotational speeds for the bottom layer deposition. The results indicate that spin-coating results in deposition of permeation layers of variable thicknesses.

10 Table III

Microchip type	Bottom layer spun at 1.5K rpm, bilayer thickness in nanometers	Bottom layer spun at 2.5K rpm, bilayer thickness in nanometers
Pt/AEAPS/agarose	587±4	465±4
	668±4	465±4
	668±3	---
PtSi/AEAPS/agarose	744±17	511±4
	685±1	620±5
		494±90

The chips as fabricated in this example, were tested for resistance to delamination. For the platinum electrode microchips, 9 electrode pads were individually addressed from two separate chips in 50 mM fresh Histidine buffer. These pads showed consistent delamination past the second two-minute direct current pulse of 500 nA/ 80 μm pad (0.1 nA/μm²) (Fig. 5A). In contrast, 6 pads were individually addressed from 2 of the PtSi microchips under the same conditions. These PtSi pads had no delamination up to several μA/pad (Fig. 5B). Thus, the PtSi electrode using the AEAPS attachment linker provided protection from delamination.

20 Example 3

In this example, data is presented showing that the covalent attachment method of the invention using PtSi electrodes, agarose and aminopropylsilanes also protects against

delamination of the permeation layer under alternating current conditions. Here, Pt and PtSi microchips bonded to the permeation layer with AEAPS were tested using two pulsed biasing protocols.

Both protocols were carried out using 50 mM L-Histidine buffer. Specifically, in protocol A, the microchips were biased at +800 nA/pad ($0.16 \text{ nA}/\mu\text{m}^2$) for 38 milliseconds (ms), -800 nA/pad for 25 ms, cycled for a total of 25 seconds using 3 pads each pulse. In protocol B, the microchips were biased at +1.6 $\mu\text{A}/\text{pad}$ ($0.32 \text{ nA}/\mu\text{m}^2$) for 19 ms, -1.6 $\mu\text{A}/\text{pad}$ for 12 ms, and cycled for a total of 14 seconds each on 3 pads addressed simultaneously. Images were taken using an INM 100 confocal microscope (Leica).

Figure 6A shows Pt chips that were biased using protocol A, followed by 0, 4, 8, 12 or 16 repeats of protocol B. The images show that delamination begins after 8 repeats of protocol B. In contrast, the PtSi chips (Fig. 6B) showed delamination to a much less extent at the 8th biasing. In order to more accurately define the delamination threshold, the chips were assayed with smaller stringency increments using biasing repeats of 2, 4, 6, and 8 times. On Pt electrodes, delamination began to occur at bias repeat number 6 (Fig. 7A). In contrast, the PtSi chip showed less delamination effect at the same level of electrodynamic stress (Fig. 7B).

The overall results indicate that damage begins to occur during the sixth application of the above protocol B and that the delamination increased with increasing cycle repeats. This delamination effect was less prominent in the PtSi chips.

Example 4

In this example, methacryloylsilanes are employed as linkers for attaching synthetic permeation layers such as acrylamide-based hydrogels to Pt and PtSi chips. Additionally, the integrity of the permeation layer was examined using a technique wherein glass beads are applied to the surface of the permeation layer as a reference upon which the confocal microscope can focus. This enables permeation layer thickness determination and facilitates the monitoring of permeation layer distortions due to such things as delamination.

Figure 8 shows a Pt microchip having an agarose permeation layer wherein the thickness of the layer before electronic biasing was determined to be $3.0 \pm 0.5 \mu\text{m}$. The figure shows the focal point at the position of the beads above the electrode. Thus, the underlying electrode is

slightly out of focus. Figure 9, the same electrode during a bias at +200 nA ($0.04 \text{ nA}/\mu\text{m}^2$) with direct current without observable distortion of the permeation layer. The beads migrate to the electrode due to the positive bias. Following this two-minute bias, the impulse was terminated and the electrode observed for changes in its appearance. As seen in Fig. 10, the beads resting over the center of the electrode moved to a location $4.0 \pm 0.5 \mu\text{m}$ above the electrode based on the vertical shift required to bring said beads back into the focal plane. Thus, the permeation layer underwent a $1 \mu\text{m}$ expansion. As shown in Fig. 11, this expansion appears to be related to the delamination of the permeation layer from the electrode (microdelamination) as indicated by the presence of concentric rings visible at the edges of the electrode pad. Additionally, in other experiments, not shown, we have observed permeation layer thickness distortions from 2 to $6 \mu\text{m}$ occurring with delamination.

In another experiment, acrylamide-based hydrogel permeation layers anchored to PtSi electrodes via the MOTS linker were exposed to a +200 nA ($0.04 \text{ nA}/\mu\text{m}^2$) bias for 2 minutes and examined for delamination. Fig. 12 shows beads resting atop the permeation layer $6 \mu\text{m}$ above the electrode surface. The beads remained at the same position above the electrode after bias shut-off, indicating that no distortion of the permeation layer occurred. Fig. 13 shows the same pad with the focal point positioned at the electrode. No delamination ringlets were observed. When the electrodynamic stress was increased to +5 μA ($1 \text{ nA}/\mu\text{m}^2$) for 2 mins., the permeation layer was observed to distort such that the layer seemed to swell. However, no delamination from the electrode was observed. The results of the above experiments are shown in Table IV.

Table IV

chip type	bias conditions (current densities)	dry thickness	initial wet thickness	post address distortion	integrity of electrode/permeation layer bond
Pt/agarose	200nA, 2 min ($0.04 \text{ nA}/\mu\text{m}^2$)	0.80 ± 0.01	3.0 ± 0.5	4.0 ± 0.5	delamination & distortion
	200nA, 2 min ($0.04 \text{ nA}/\mu\text{m}^2$)	0.80 ± 0.01	3.0 ± 0.5	6.0 ± 0.5	delamination & distortion
Pt/polyacrylamide	200nA, 2 min ($0.04 \text{ nA}/\mu\text{m}^2$)	2.0 ± 0.1	5.0 ± 0.5	9.0 ± 0.5	delamination & distortion
	200nA, 2 min ($0.04 \text{ nA}/\mu\text{m}^2$)	1.9 ± 0.1	5.0 ± 0.5	9.0 ± 0.5	delamination & distortion

PtSi/polyacrylamide	200nA, 2 min (0.04 nA/ μm^2)	2.0 \pm 0.1	5.0 \pm 0.5	5.0 \pm 0.5	intact
	500nA, 1 min (0.1 nA/ μm^2)	2.0 \pm 0.1	6.0 \pm 0.5	6.0 \pm 0.5	intact
	1 uA, 2 min (0.2 nA/ μm^2)	2.0 \pm 0.1	6.0 \pm 0.5	6.0 \pm 0.5	intact
	2 uA, 2 min (0.4 nA/ μm^2)	2.0 \pm 0.1	6.0 \pm 0.5	6.0 \pm 0.5	intact
	5 uA, 2 min (1 nA/ μm^2)	2.0 \pm 0.1	6.0 \pm 0.5	12.0 \pm 0.5	distortion without delamination

Given that these results show that current densities in the range of 1 nA/ μm^2 are useful in the operation of microchips having bonding chemistry resistant to delamination, we further contemplate that current densities in the range of at least 10 nA/ μm^2 may be used with microchips having permeation layers which are bound to the electrodes using the bonding chemistry of the present invention without delamination.

Modifications and other embodiments of the invention will be apparent to those skilled in the art to which this invention relates having the benefit of the foregoing teachings, descriptions, and associated drawings. The present invention is therefore not to be limited to the specific embodiments disclosed but is to include modifications and other embodiments which are within the scope of the appended claims. All references are herein incorporated by reference.